VIBRATION AND NOISE ENVIRONMENTAL STUDIES FOR PROJECT MERCURY*

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SUMMARY

Several of the vibration and noise studies conducted for the Mercury capsule and its components are described. Particular attention is given to the experimental techniques used and the main results obtained.

Laboratory vibration data for a full-scale capsule both on a large vibration exciter and in the presence of a noise field are presented along with vibration measurements obtained during the flight readiness firing at Cape Canaveral and during a portion of an actual flight.

Acoustic measurements are presented of internal and external noise environments during the launch and free-flight conditions of the capsule. Particular attention is given to a discussion of a unique series of noise environmental tests of a full-scale manned capsule. These environmental tests were accomplished by utilizing the exhaust of a large blowdown-type wind tunnel as the noise source to simulate the rocket motor noise at lift-off and the aerodynamic noise during the exit flight phase. Other topics dealt with briefly are capsule noise transmission characteristics, surface shingle sonic fatigue tests, and exploratory communication studies in the presence of intense noise.

INTRODUCTION

With the advent of Project Mercury, manned flight in the adverse environments of space is becoming a reality. The nature of the space environment is, in general, subject to further study before its severity and full effects on the design of space flight systems are well established, but it is clear at present that the Mercury Capsule will be subjected to some potentially serious vibration and noise environments. The vibration and noise problems arise from obvious sources; namely the use of powerful engines, the high airspeeds attained within the earth's atmosphere, and the need to save weight in the basic structure of the capsule in order to accommodate the maximum payload. In order to assure a successful flight, there is need for maintaining the integrity of the capsule structure and for improving the reliability of its sensitive control equipment. There is also need to control the inside noise environment of the capsule to insure the safety of the occupant, to allow him to communicate with the ground stations, and to perform other assigned duties.

At present, only small quantities of data exist that indicate the vibration and noise levels to which the Mercury capsule will be subjected. These data were obtained from ground vibration studies, noise simulation studies, flight readiness firings, and during flights of the Big Joe, Little Joe, and MA-1 vehicles. The results of some of these studies have been partially reported elsewhere (refs. 1, 2, and 4). The purpose of this paper is to summarize and review some of the vibration and noise studies carried out during Project Mercury to ascertain and to improve, if necessary, the reliability of the system to withstand the environmental forces to which it will be subjected during flight.

The paper is divided into two parts as indicated in table I.

TABLE I

MERCURY CAPSULE ENVIRONMENTAL STUDIES

Vibrations
Sources of vibrations
Resonance tests on capsule
Ground-based vibration tests
(a) Response to high-intensity noise pressures
(b) Response to booster thrust forces
In-flight vibration measurements
Acoustics
Test vehicles
Measured in-flight noise environment
Full-scale noise environmental tests
(a) Test procedures
(b) Capsule transmission loss characteristics
(c) Communications
Sonic fatigue

The first part deals with some of the vibration studies on the Mercury capsule and includes a discussion of various sources of vibratory input forces and a description of resonance testing of the capsule with electromagnetic shakers. Also discussed are two significant ground-based vibration studies. One study consisted of an investigation of the vibratory response of the capsule structure to high-intensity noise pressures which were generated on the capsule by locating it on a soft mount near the exhaust of a large blowdown-type wind tunnel at the Langley Research Center. The other study concerned the measurement of vibration levels obtained during the MA-1 flight readiness firing at Cape Canaveral. The first part of the paper is concluded with a discussion of the vibration data measured during the MA-1 flight of the Mercury-Atlas capsule.

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The second part of the paper treats additional acoustic excitation studies. A description is given of three rocket-powered test vehicles, two of which were used to obtain the in-flight noise environment and the other to obtain the noise level of the Atlas during take-off. Some representative measurements of the acoustic environment are given. Then follows a description of a full-scale noise environmental test including a discussion of the test procedures and some representative results. These results include a description of the capsule noise transmission characteristics and some discussion of the problems of voice communications between the capsule occupant and ground stations. This part of the paper is concluded with a discussion of the fatigue of shingles on the outer surface of the capsule due to acoustic excitation.

VIBRATIONS

Some Sources of Vibratory Input Forces

There are several sources of mechanical vibration in the Mercury-Atlas system which are common to space flight systems. Prior to engine ignition, the unbalance of rotating components such as pumps, generators, etc., are sources of vibrations. Engine ignition itself imposes high vibratory loads on the system. Immediately after engine firing and during lift-off, vibratory loads are caused by turbine chugging, pulsations of engine thrust, acoustic pressures associated with the engines, and gimballing of the engine in response to control forces. As the exit phase of flight continues, fuel sloshing is another source of vibratory input forces as is also boundary-layer noise and the aerodynamic forces arising from gusts, wind shears, turbulence, shock wave pulsations, and flow separations. Additional vibratory forces occur during capsule separation due to the use of various devices such as explosive bolts and separation rockets. Thus, it is clear from the foregoing remarks that there are many sources of random, sinusoidal, and transient vibratory input forces which lead to vibrations in the system.

Resonance Tests on the Capsule

Vibration testing is usually conducted by imposing either separately or collectively sinusoidal and random vibratory forces on the structure by means of shakers. Sinusoidal vibration inputs are generally used to locate natural frequencies of the system or of its components and thereby detect amplification factors. Both sinusoidal and random-force inputs are used to simulate the flight vibration environment, to check for fatigue and to help ascertain the integrity of the entire system. The use of a small shaker is shown in figure 1. The shaker is attached to the end of the payload for exciting resonances of the pylon and escape rockets. The pylon is suspended on elastic cables (shock cord) to support its weight and the base of the capsule is secured to a mounting base. Vibration pickups or accelerometers strategically located are used for the determination of the displacement amplification factors which in turn determine where localized "fixes" in the form of adjustments of the mass and stiffness of the structure are made.

Figure 2 shows the capsule of the MA-1 configuration mounted above a large shaker. In this case, the pylon has been removed and replaced with a stub tower. The shaker was rated at 7,400 pounds vector force with both random and sinusoidal excitation capabilities. The weight of the complete flight system is supported by elastic cables. The safety stand shown is for protection of the capsule and exciter in case of cable failure. Accelerometers were used for the determination of the response of the system to applied excitation forces over a wide range of frequencies. Stroboscopic lights were also useful for the determination of the low-frequency, high-amplitude responses. An example of the displacement amplification factors obtained on Mercury-Atlas Capsule No. 1 (MA-1) is given in figure 3. The amplification factor A is shown as the ordinate and the frequency is shown as the abscissa. The curves present the amplification factors obtained on a couch support panel when shaken in the Z direction as shown in the insert. The solid curve pertains to the longitudinal (Z), or flight direction and the dashed curve pertains to the transverse (X) direction. The figure shows that at a frequency of 70 cps, an amplification factor of 6.2 is obtained in the longitudinal direction and an amplification factor of 2.1 is obtained in the transverse direction. An amplification factor of 6.2 represents a substantial vibration of the structure and was considered to be unacceptable. As a result, a stiffener was attached to the panel approximately in the location of the accelerometers to increase the resonant frequency and reduce the vibration levels.

The aforementioned example represents only one typical case where environmental tests pointed out potential weaknesses in the structure and indicated simple fixes. A more significant result was recently obtained when it was found that the natural frequencies of the panels and supporting structure of the Atlas adapter were approximately equal; a situation which resulted in substantial resonance amplification of a breathing mode of the adapter structure when the panels were excited at their natural frequencies. This situation was considered undesirable and was eliminated by increasing the stiffness of the annular rings within the adapter.

Ground-Based Vibration Tests

Response to high-intensity noise pressures.- As previously mentioned, the high-intensity noise pressures due to either engine thrust or aerodynamic forces are primary sources of structural vibration. The noise or acoustic pressures from the engine are primarily significant during lift-off and subsonic flight, whereas at the higher Mach numbers corresponding to the maximum dynamic pressures, the aerodynamic noises associated with the boundary layer are predominant. Measurements have been made and will be discussed later in the paper which indicate the resulting acoustic

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pressure levels. In order to obtain an insight as to the magnitudes of the vibrations induced by these noise pressures, a manned capsule was soft-mounted in an intense noise field which simulates the maximum aerodynamic noise anticipated during the exit phase of flight. Figure 4 shows the location of the capsule (position 2) relative to the noise source which was the 9- by 6-foot thermal structures blowdown-type tunnel at the Langley Research Center. The figure also shows the various noise level contours. During these tests the capsule was occupied by an astronaut, and various sub-systems such as telemetry, communications, etc. were closely monitored to determine the ability of the occupant to perform his duties as well as to evaluate the operational characteristics of the system while subjected to the noise environment. Vibration pickups were located inside and outside the capsule as well as on the pylon. The internal vibration levels measured with a triaxial accelerometer are shown in figure 5. The location of the accelerometer and the orientation of the principal axes are indicated by the sketch of the capsule-tower configuration also shown in the figure. The curves shown in the figure present the reduced random acceleration data as a function of frequency and indicate that the acceleration levels in the three mutually perpendicular directions are the same order of magnitude. It is significant that the maximum values of the internal accelerations as indicated in the figure were approximately 1.5g.

Response to booster thrust forces.- Another method used to determine the vibration levels due to acoustic excitation was to obtain vibration data during static firings of the booster. Prior to launching a Mercury-Atlas (MA-1) capsule, the Atlas booster was test fired while restrained on the launching pad as shown in figure 6. During the test firing of the booster, the outputs of the longitudinal and normal accelerometers located within the capsule on the left-hand trunnion were recorded on tape for later analysis, and the results of power spectral density analysis of the measured accelerations are given in figure 7. The figure shows the "power," g squared per cycle per second, as a function of frequency. The solid curve represents the power levels in the longitudinal direction and the dashed curve represents power levels in the normal direction. The power spectral density levels are given for 3 seconds of engine burning and were obtained by use of a filter whose bandwidth was 4 cycles per second. The overall vibration levels obtained by determining the rms area under the curves are about 3g rms. For purposes of comparison, the equivalent power levels associated with the acoustic noise test results shown in figure 5 are also of the order of magnitude of 3g rms.

Flight Vibration Measurements

The most desirable vibration data are those obtained during actual flights of the capsule. During the short flight of the MA-1, one channel each of longitudinal, normal, and transverse vibration data were telemetered from the interior of the capsule, and the results of the analysis of the data are shown in figures 8 and 9. In figure 8, the solid curve shows the longitudinal vibratory accelerations during the interval of 40 to 45 seconds of flight, and the dashed curve shows the longitudinal vibratory accelerations in the time interval of 53.5 to 58.5 seconds of the flight. The ordinate, average peak acceleration in g's refers to the average of the peak accelerations during the indicated time increments. Due to the limitation of the frequency response of the accelerometers, the upper frequency is limited to about 200 cps. The analyzer bandwidth used in reducing these data was one cps. The figure shows that the highest accelerations occur at low frequencies, and as the burning time progresses, there appears to be a decrease in these accelerations. Although a direct comparison cannot be made with the data of figure 5 (different capsules on different suspensions) it is of interest that the measured accelerations are of small magnitude under both conditions.

The normal and transverse accelerations measured during the time interval from 53.5 to 58.5 seconds of flight are shown in figure 9. The ordinate is again the peak acceleration and the abscissa is the frequency in cps. The width of the band-pass filter used in reducing these data was four cycles per second. In this case, the response of the accelerometers limits the accurate reproduction of the accelerations to those which occur at frequencies below 35 cps. Above 35 cps, the accelerometer response is no longer flat, but decreases in sensitivity with frequency and indicates accelerations which are somewhat below those actually encountered. The measured values of acceleration are very low, less than 0.15g in the range of frequencies shown.

Since no flight data were obtained at frequencies above 200 cps due to the low response of the accelerometers used for obtaining these data, a comparison of acceleration levels at the higher frequencies cannot be made. Future flights of the capsule will have among its instrumentation additional higher frequency response pickups for obtaining in-flight vibration data. In addition, a dual-channel flight spectrum analyzer will be used, making it possible to telemeter the high-frequency acceleration data at low frequency in the analyzed form. One channel will be used to transmit vibration measurements in the frequency range to 2,000 cps, and the other channel will be used to transmit acoustic data in the frequency range to 10,000 cps.

ACOUSTICS

Test Vehicles

In order to obtain the noise environment for the Mercury capsule, microphones were mounted on three test vehicles which are shown in figure 10. The vehicles shown are the Big Joe which was fired from Cape Canaveral, Florida, and the Little Joe 2 and Little Joe 1B vehicles which were fired from Wallops Island, Virginia (ref. 1). The approximate locations of both external and internal microphone stations are indicated. The internal microphones were located at the position where the pilot's head would be located, approximately 6 inches from the capsule side wall. The flight data were recorded with the aid of on-board tape recorders which were recovered after the flights. It should be noted that the performance parameters, Mach number, free-stream dynamic pressure, etc., of the three vehicles differ; the Atlas being a liquid-fueled, relatively low-acceleration booster while the Little Joe boosters are solid-fueled, high-acceleration vehicles. Also, it can be seen that the external geometries of the three vehicles are somewhat different.

Measured In-Flight Noise Environment

As an example of the type of data that have been measured in the Mercury support vehicles previously shown, a time history of the internal capsule noise as measured on the Big Joe 1 vehicle is presented in figure 11 (ref. 1). Data are shown for the launch and subsequent free-flight operations of the vehicle with some of the more significant events such as launch, exit maximum dynamic pressure, booster and sustainer cutoff, maximum dynamic pressure in reentry, and deployment of drogue and main parachutes indicated. It should be noted that the maximum sound-pressure levels occurred during maximum dynamic pressure during exit and are believed to be of aerodynamic origin.

In addition to the data illustrated in figure 11, similar data which were recorded on the Little Joe 1B vehicle are presented in figure 12. Shown are the time histories of the internal and external noise, both on the same time base (ref. 2). Significant events such as launch, maximum dynamic pressure, and abort phase are again indicated. Looking at the top half of the figure which is an overall time history of the internal noise, it can be seen that, as in the case of the Big Joe capsule, the highest sound-pressure levels were recorded during the time that the vehicle was operating in the region of maximum dynamic pressure. Of special interest is the external overall noise time history obtained for Little Joe 1B as shown in the lower half of figure 12. It can be seen that the maximum sound-pressure levels measured externally occur at an earlier time than those measured internally. However, it is believed that the pressures measured at a point on the surface are closely related to the local flow conditions and vary as a function of Mach number. They would thus vary at a given external point as a function of time and at a given time would be different at different measuring stations. A distinguishing characteristic of the external noise is the presence of a low-frequency, relatively large-amplitude disturbance whose peak occurs while the vehicle is still in subsonic flight. These external data are shown in a different manner in figure 13 where the ratio of sound pressure to dynamic pressure is shown as a function of Mach number.

It can be seen that the external sound pressures were much higher than would have been expected, the line of small dashes representing the maximum values that would be estimated on the basis of available wind-tunnel and low-speed flight data for an aerodynamically clean vehicle (ref. 3). This large increase in sound pressure is thought due to turbulent boundary-layer flow, flow separation, shock interaction, etc., caused by the escape rocket and tower and the aerodynamic spoiler located at the base of the tower.

Although the external data of figures 12 and 13 were measured at only one point on the vehicle surface, there is reason to believe, based on related wind-tunnel studies, that such large acoustic pressures exist over the entire capsule and to some extent on the booster at some time during the exit phase of a flight.

Full-Scale Noise Environmental Tests

Since the noise measurements made on the three Mercury test vehicles indicated higher levels than had been anticipated, it was decided that a production Mercury capsule should be exposed to an intense noise environment simulating actual flight conditions in order to determine the effects on the primary capsule structure, sensitive control equipment, and communications between the astronaut and ground control. It was decided to simulate first the noise due to the Atlas engines at lift-off and second the most intense aerodynamic noise expected during the exit phase of a flight. The octave band spectra representing these two conditions are presented in figure 14. The dashed line is the measured spectrum of an Atlas booster recorded in the vicinity of the capsule during static firing (ref. 1), and the solid line represents the spectrum of the maximum aerodynamic noise estimated for the Mercury vehicle based on available flight data (ref. 4).

Test procedures.- In order to simulate the preceding conditions, a production Mercury capsule was tested in the noise field produced by the exhaust of a 475,000-pound thrust blowdown wind tunnel which is located at the Langley Research Center. A picture of this facility, the 9- by 6-foot thermal structures tunnel, is presented in figure 15. The large storage tanks at the left supply air at pressures above 400 psi to a heat exchanger which drys the air and elevates its temperature somewhat. The air is then passed through the test section and exhausted to the atmosphere through the diffuser section shown at the right of the figure. Running times of approximately 15 to 20 seconds are available. A plan view of the test area along with a few representative constant sound-pressure level contours is presented in figure 4 (ref. 5). It can be seen that, in the immediate vicinity of the diffuser exit, sound-pressure levels of up to 162 db have been measured. As the distance from the exit is increased the sound-pressure levels decrease. However, it can be seen that levels in excess of 150 db exist over a relatively large area, thus permitting the acoustic testing of large objects. It is also of interest to note that if a constant sound-pressure level contour line is followed away from the exit, the spectrum will change. Close to the exit the spectrum is rather flat in nature but as the distance from the exit is increased, the high frequencies begin to decrease and the low frequencies to increase.

By using data gathered during previous sound surveys made around the tunnel, it was possible to pick positions in the noise field where the levels and spectra produced during a tunnel run would approximate the spectra as indicated in figure 14. The two positions chosen are indicated in figure 4, position 1 being used for the Atlas rocket engine spectra and position 2 for the aerodynamic spectra. In order to minimize handling problems, the Mercury capsule was mounted on a flat-bed trailer using a special mounting rig as shown in figure 16. The capsule was positioned in the rig, with the tower parallel to the ground, by the use of coil springs which effectively isolated the capsule from the mounting rig and trailer structure. With the capsule mounted on the trailer the task of repositioning in the noise field was greatly simplified.

The octave band spectra of figure 17 indicate the degree of simulation obtained at both positions. The test data shown were recorded during the tests by three microphones located 120° apart around the circumference of the capsule. For all tests the noise field around the capsule was found to be of uniform level, measurements varying only 1 or 2 db between microphones.

For the Atlas rocket engine noise simulation, the fully instrumented production Mercury capsule was placed in position 1 and an 18-second tunnel run was made. The resulting spectrum for this test is shown by the dashed line in the upper half of figure 17 and is seen to simulate closely the measured Atlas spectrum represented by the solid line. All capsule on-board systems were operating and being monitored during the test, and no malfunctions due to noise were noted. The capsule structure was given a thorough examination for fatigue failures after the test with negative results.

Upon completion of the test at position 1, the capsule was moved to position 2 for the aerodynamic noise simulation and the results are indicated in the lower half of figure 17, the solid line being the desired aerodynamic spectrum and the dashed line being the spectrum measured during the tests. Although the simulated spectrum was somewhat lower than the desired spectrum at the lower frequencies, it was felt that the test was adequate at the frequencies of concern for the capsule structural integrity, operation of on-board systems, and communications. Three 18-second runs were made at position 2, and no equipment or structural failures were noted due to noise.

Capsule transmission loss characteristics.- Of interest concerning the operation of capsule on-board equipment and communications between the capsule occupant and ground stations are the capsule attenuation characteristics as shown in figure 18. The solid line represents the average external environment for two of the three runs at position 2 and the line of small dashes represents the corresponding internal measurements. The shaded area between these two curves is an indication of the noise transmission loss associated with the capsule structure. Shown for comparison by the line of large dashes is the internal spectrum that would be estimated using the mass law. It can be seen that more noise reduction occurred at the lower frequencies than would be predicted by the pure inertia considerations of the mass law (ref. 6). It is believed that these results are due to stiffness effects caused by the characteristic shape of the capsule.

Communications.- Preliminary laboratory tests have indicated that communications would be marginal in the presence of noise levels in excess of 120 db for the type of spectrum anticipated and the type of personal equipment proposed. In order to provide a full-scale check of the capsule communication equipment and procedures, the opportunity was taken to include an astronaut in the capsule during one of the noise tests at position 2. The run was made with the astronaut in the capsule using a production version of the Mercury suit operating on the capsule's environmental control system. During the run voice communications were established between the astronaut and the control trailer via the capsule's UHF communications link. Voice communications both into and out of the capsule were clearly readable during the test, and no malfunctions of the capsule environmental or control systems occurred due to the noise environment. The astronaut likened the noise during the test to that experienced by a pilot during an afterburner take-off.

Sonic Fatigue

Although sonic fatigue is not believed to be of serious concern for the present design of the Mercury capsule, some interesting results came out of the development testing as illustrated by the photograph of figure 19. Shown is an example of an early design of the skin surface heat shield shingle of 0.010 gage stainless-steel construction. Two of the main features to note are the stamped-in beads running perpendicular to the direction of air flow and the oversized holes which allow for expansion due to heat. Also shown in the photo are examples of three types of failure encountered. The most obvious is the long fatigue crack at the right-hand edge in the area of the termination of the beads. Cracks were noted to originate in or near the radius of the bead, due probably to a stress concentration, and to then link up in the manner shown. Small fatigue cracks were also noted to emanate from the oversized bolt holes as indicated in the top center of the figure. Another significant result is the elongation of the bolt holes such as is indicated in the bottom of the figure. It should be pointed out that the production capsule incorporates shingles having thicker skin gage, longer beads, and somewhat different materials.

CONCLUDING REMARKS

A brief review has been presented of some of the environmental studies carried out on the Project Mercury capsule components and systems in order to determine the levels of the vibrations and acoustic environments and to ascertain the reliability of the capsule's systems in the presence of these environments.

The results of some of these environmental studies have led directly to modifications of the Atlas adapter and capsule structures which have helped to increase their integrity and reliability.

Although the studies described are related directly to Project Mercury, it is felt that the results obtained will have useful applications concerning future ground-launched, manned space vehicles.

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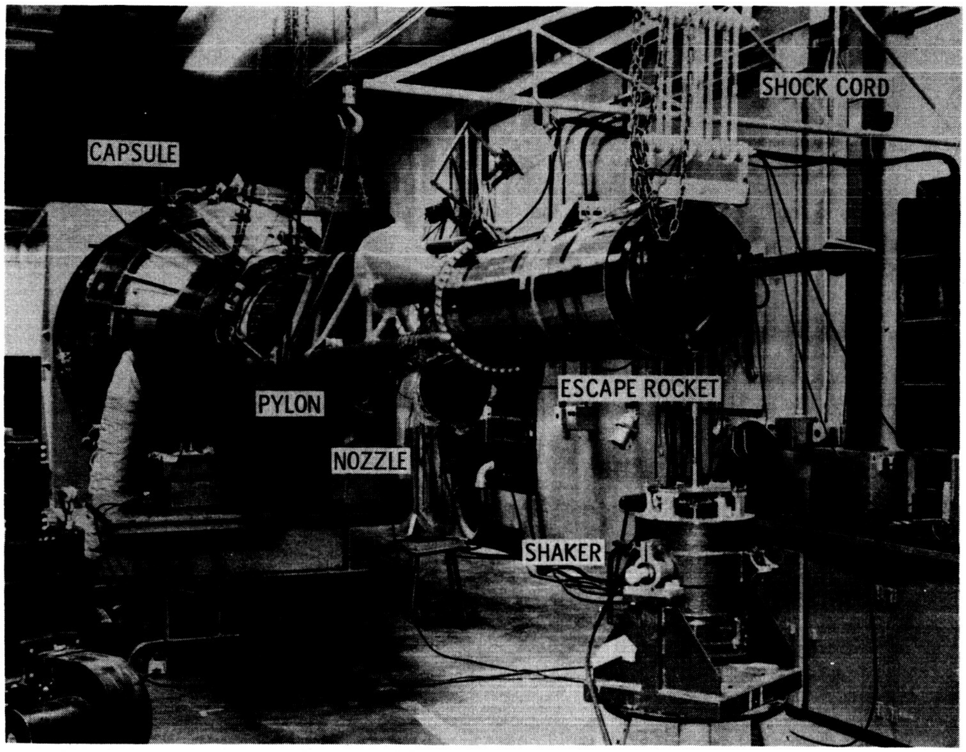

Figure 1. - Vibration test setup for obtaining resonant frequencies.

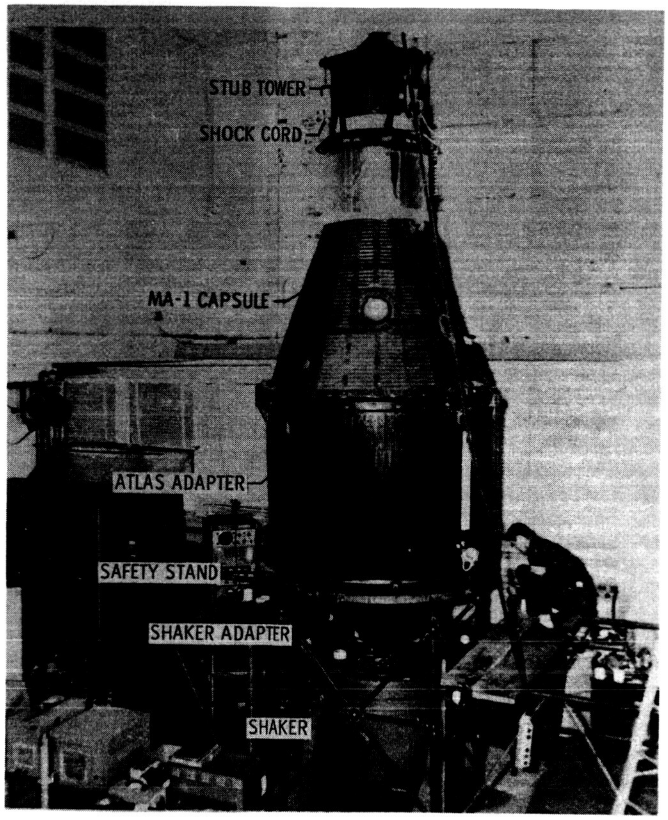

Figure 2. - Vibration test setup for subjecting the capsule to sinusoidal and random excitation.

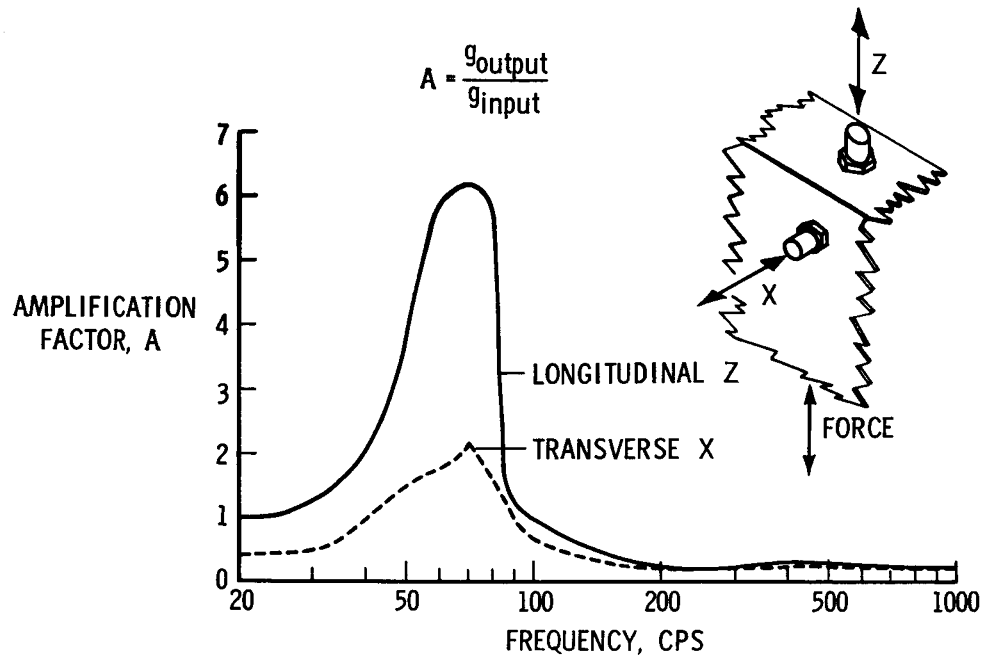

Figure 3.- Variation of couch support amplification factor with frequency. NASA

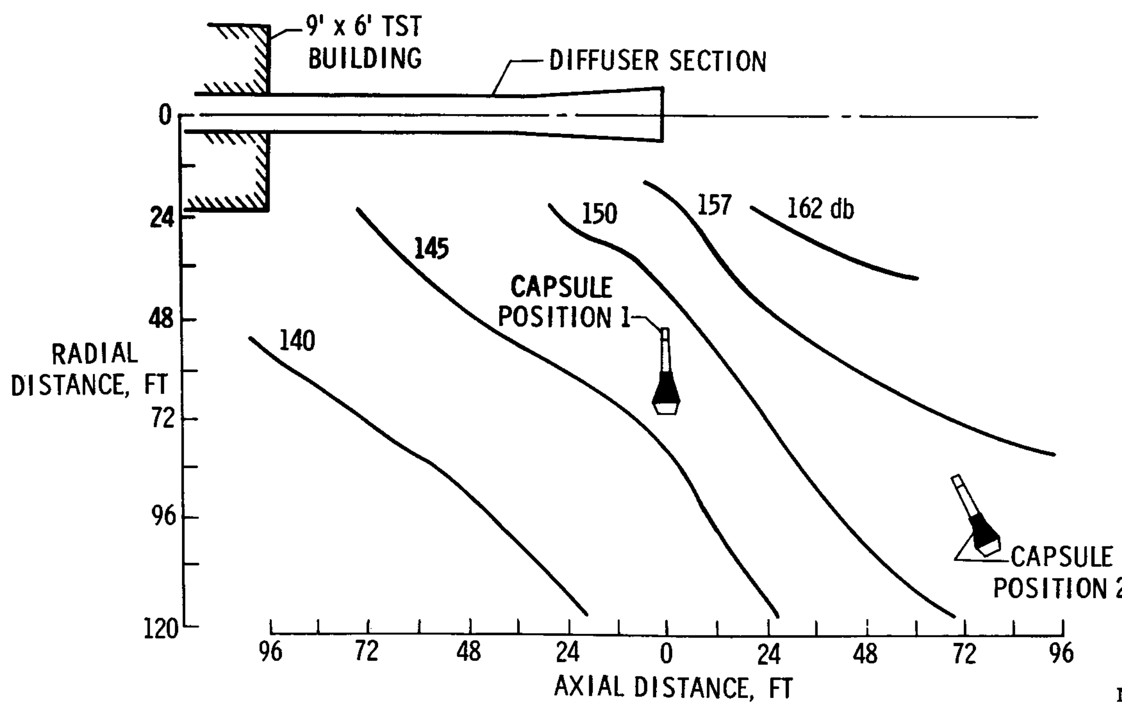

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Figure 4.- Plan view of 9- by 6-foot T.S.T. showing capsule test positions and some representative noise contours.

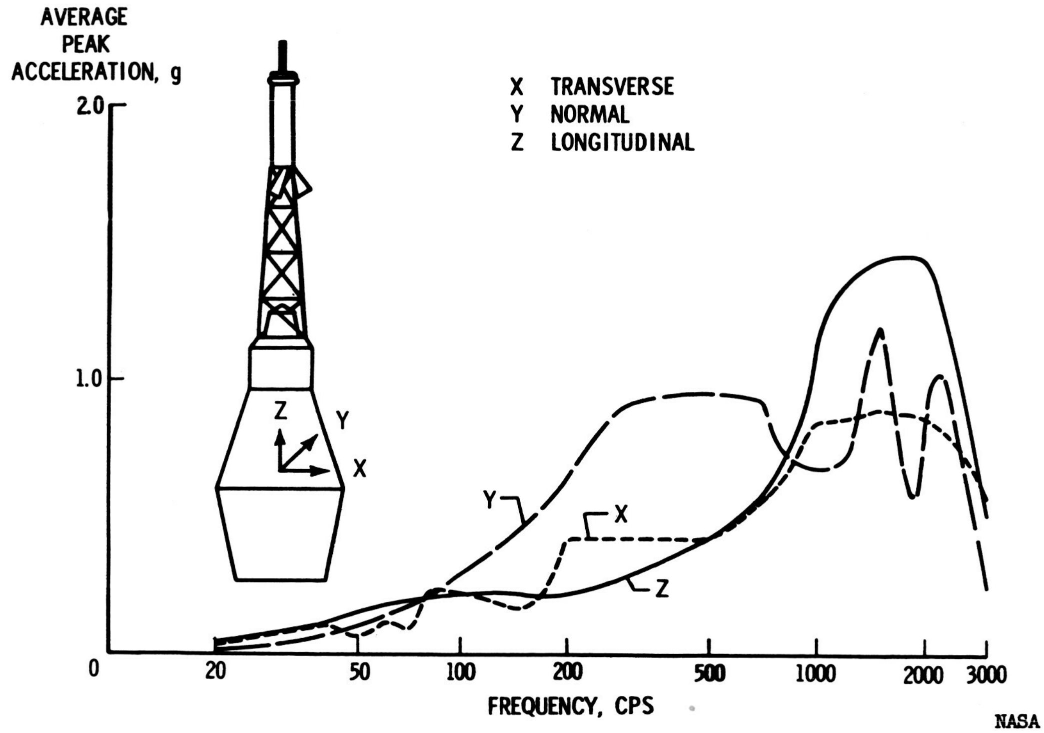


Figure 5. -Measured internal vibration levels of the Mercury capsule exposed to an intense noise field (153 db).

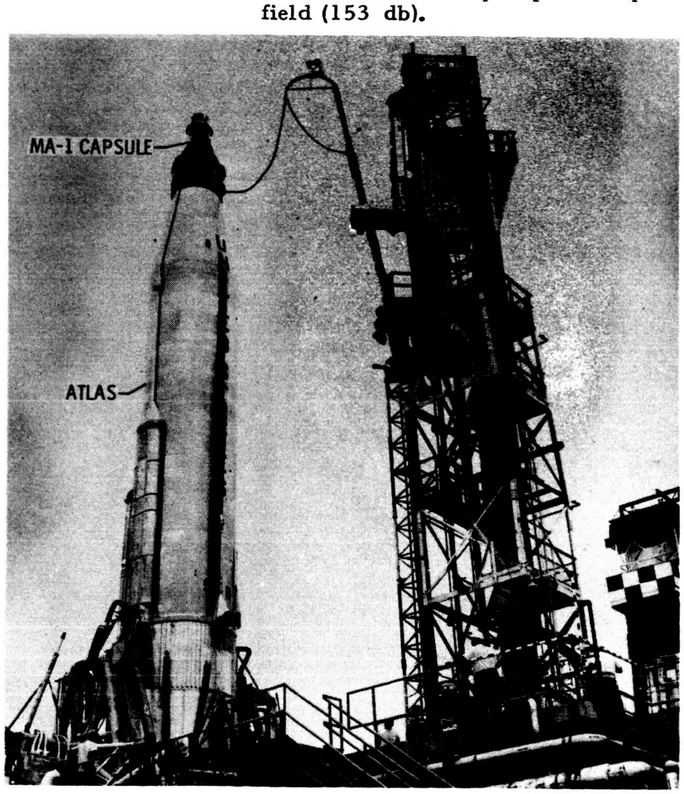


Figure 6. - MA-1 vehicle on launching platform at Cape Canaveral.

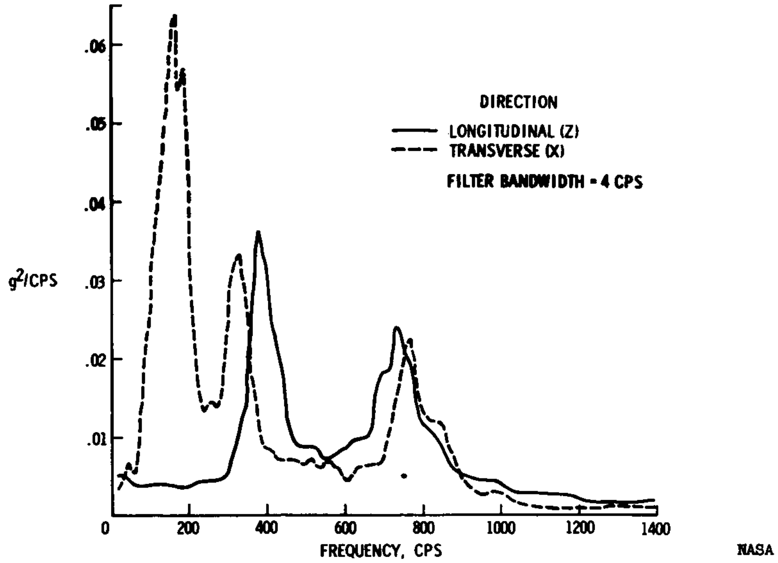


Figure 7. -Vibration data measured inside the MA-1 capsule during flight readiness firing of the booster.

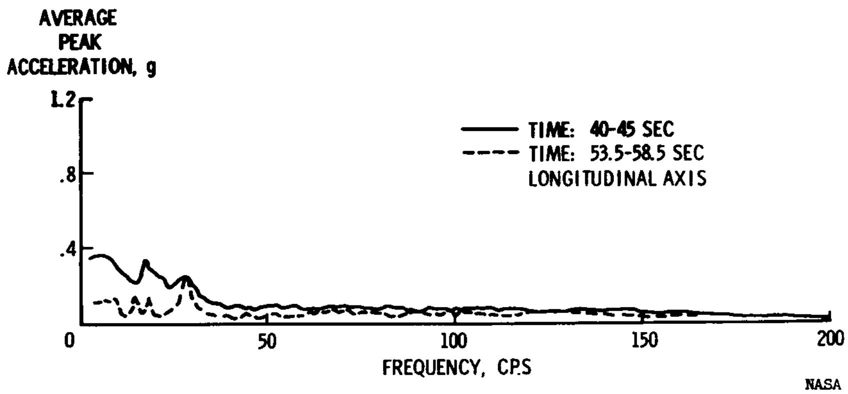


Figure 8. -Flight vibration data measured inside the MA-1 capsule, longitudinal (Z) axis.

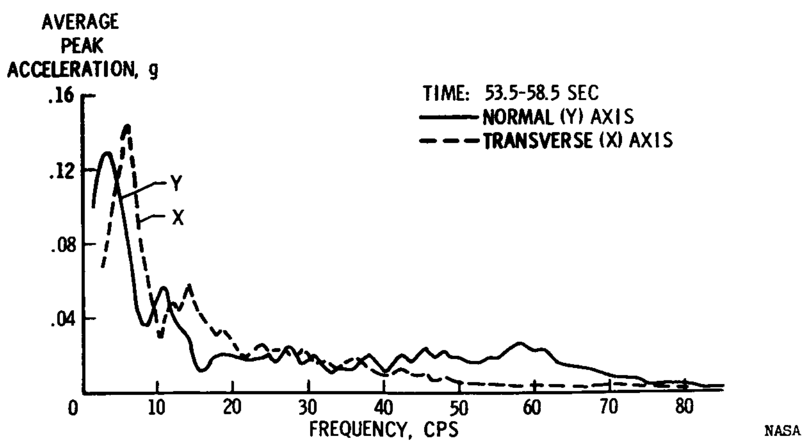


Figure 9. -Flight vibration data measured inside the MA-1 capsule, normal and transverse axis.

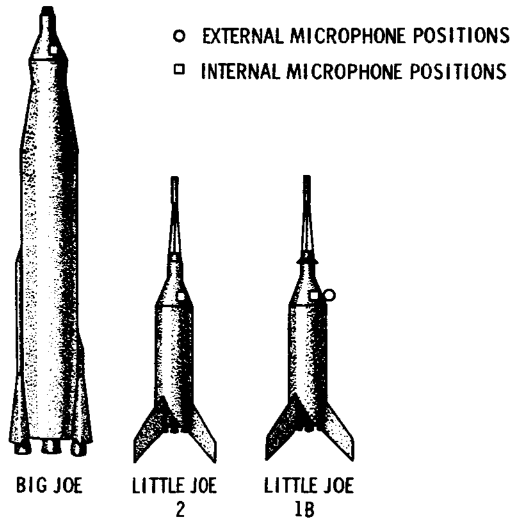


Figure 10. -Project Mercury test vehicles.

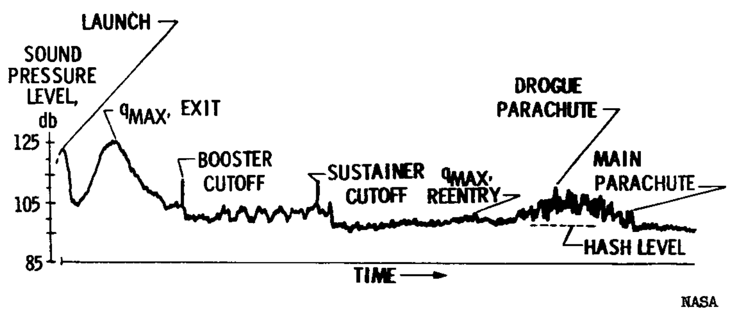


Figure 11. -Internal capsule over-all noise level time history for Big Joe.

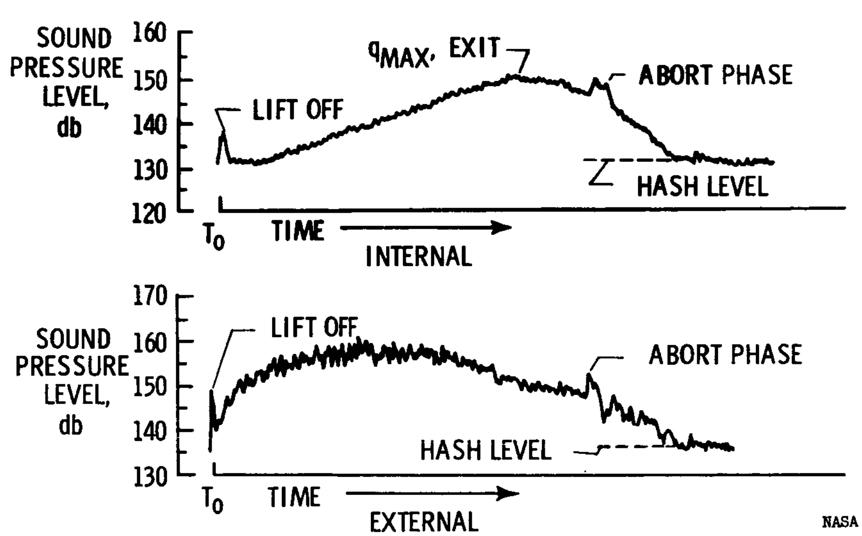


Figure 12. -Internal and external capsule over-all noise level time histories for Little Joe 1B.

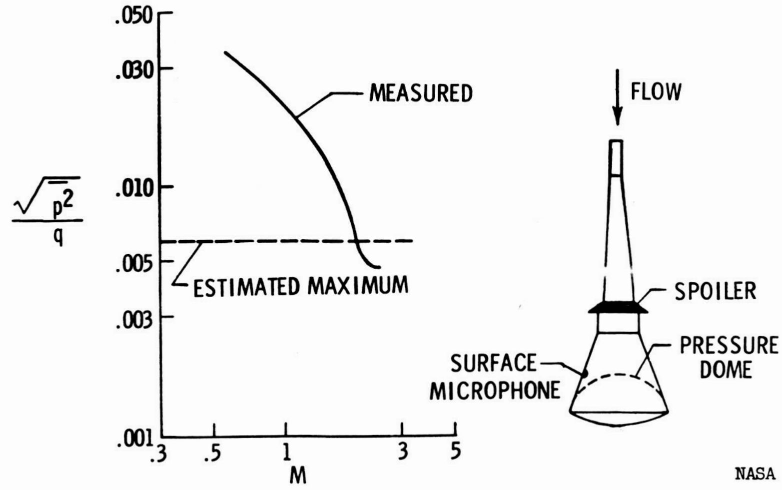


Figure 13. -External capsule noise pressures for Little Joe 1B.

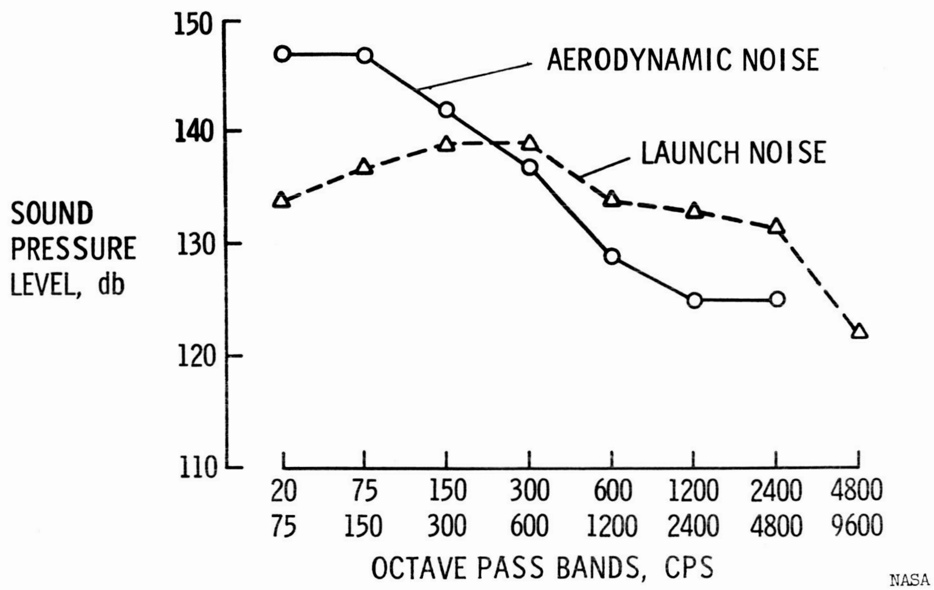


Figure 14. -Maximum external noise environments estimated for the Mercury capsule.

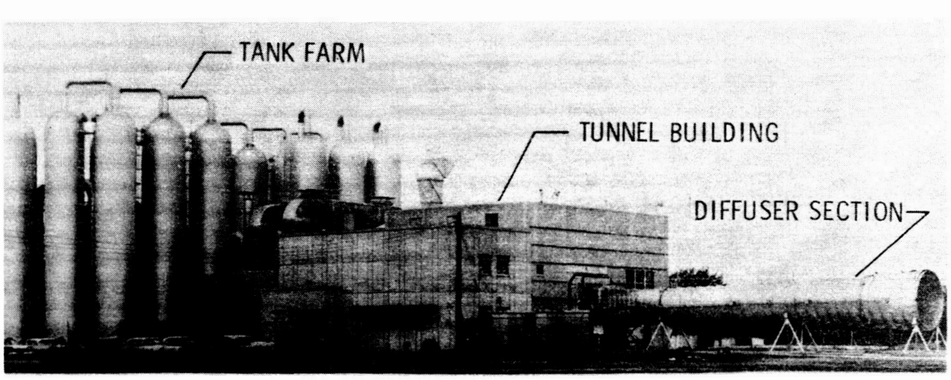


Figure 15. - Photograph of 9 - by 6-foot thermal structures tunnel.

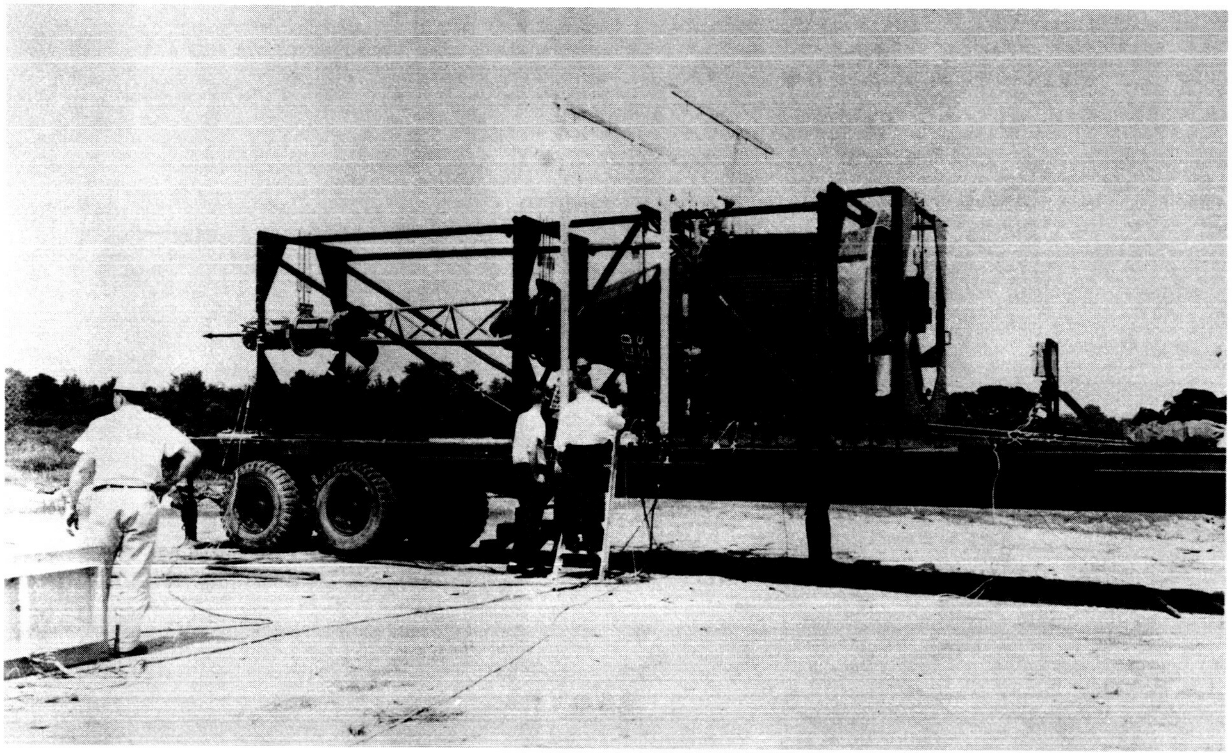
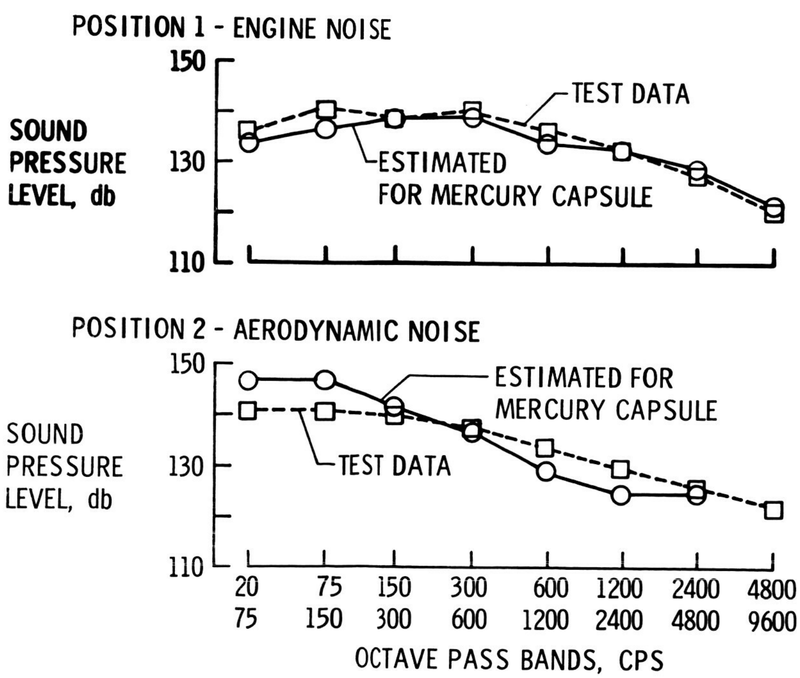


Figure 16. - Mercury capsule mounting rig for environmental noise tests.



NASA

Figure 17.- Comparison of environmental test spectra with those estimated for the Mercury capsule.

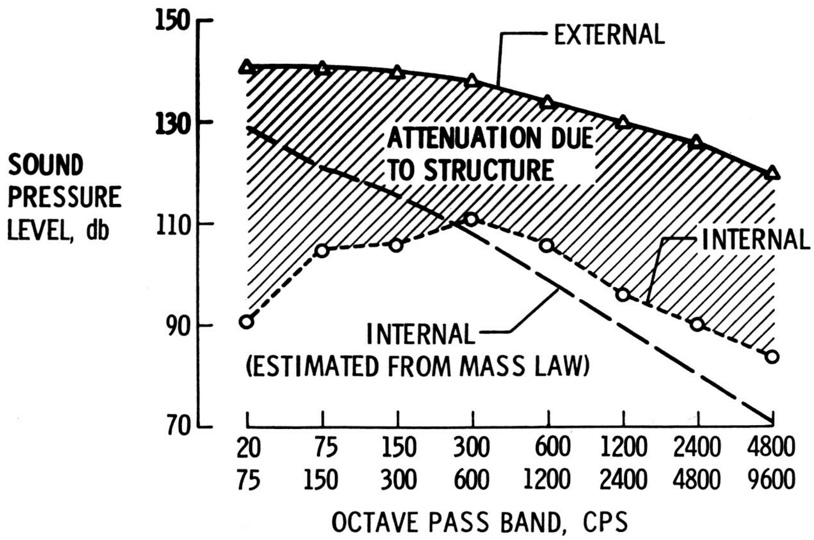


Figure 18.- Mercury capsule attenuation characteristics. NASA

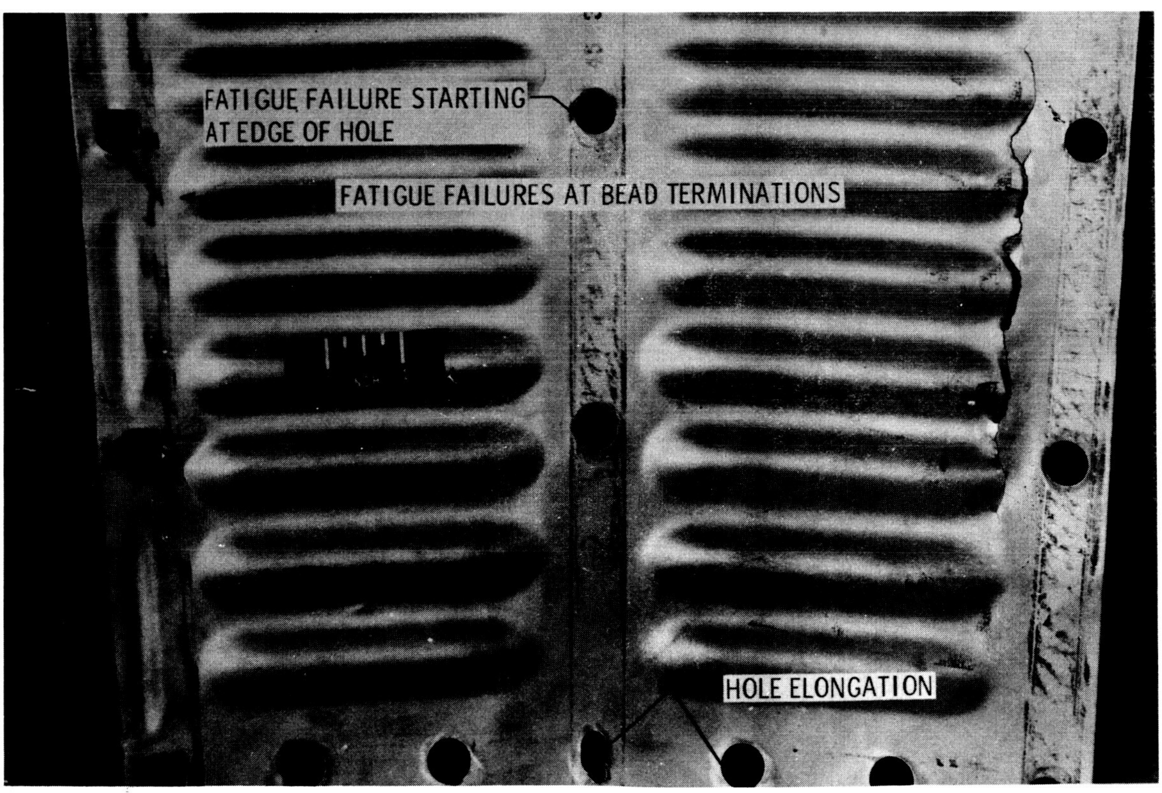


Figure 19. - Photograph of 0.010 in. Mercury shingle showing three types of failures.